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McNaull, J., Augusto, J. C., Mulvenna, M., & McCullagh, PJ. (2012). Data and Information Quality Issues in Ambient Assisted Living Systems. *Journal of Data and Information Quality*, *4*(1), 4:1-4:15. https://doi.org/10.1145/2378016.2378020



**Published in:**
Journal of Data and Information Quality

**Publication Status:**
Published (in print/issue): 01/10/2012

**DOI:**
10.1145/2378016.2378020

**Document Version**
Publisher's PDF, also known as Version of record

# Data and Information Quality Issues in Ambient Assisted Living Systems

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Demographic aging, as a result of people living for longer, has put an increased burden on health and social care provision across most of the economies of the developed and developing world. In order to cope with the greater numbers of older people, together with increasing prevalence of chronic diseases, governments are looking to new ways to provide care and support to older people and their care providers. A growing trend is where health and social care providers are moving towards the use of assisted living technologies to provide care and assistance in the home. In this article, the research area of Ambient Assisted Living (AAL) systems is examined and the data, information and the higher-level contextual knowledge quality issues in relation to these systems, is discussed. Lack of quality control may result in an AAL system providing assistance and support based upon incorrect data, information and knowledge inputs, and this may have a detrimental effect on the person making use of the system. We propose a model whereby contextual knowledge gained during the AAL system's reasoning cycle can be fed back to aid in further quality checking at the various architectural layers, and a realistic AAL scenario is provided to support this. Future research should be conducted in these areas, with the requirement of building quality criteria into the design and implementation of AAL systems.

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Categories and Subject Descriptors: I.2.7 [**Artificial Intelligence**]: Natural Language Processing

General Terms: Design, Management, Human Factors

Additional Key Words and Phrases: Ambient assisted living, assisted living, context-aware computing, quality of context

**ACM Reference Format:**
McNaull, J., Augusto, J. C., Mulvenna, M., and McCullagh, P. 2012. Data and information quality issues in Ambient assisted living systems. ACM J. Data Inform. Quality 4, 1, Article 4 (October 2012), 15 pages.
DOI = 10.1145/2378016.2378020 http://doi.acm.org/10.1145/2378016.2378020

## 1. INTRODUCTION

Assisted living is the term given to the provision of care to people either in their own homes or in supported housing, underpinned by technology. The provision of care, augmented by assisted living technologies, is growing because of the increasing demand and also due to the maturing of many of the underlying technologies that make assisted living possible. In parallel with this development, researchers in computing have been exploring the emerging area of ambient intelligence, which applies automated reasoning and other artificial intelligence techniques to the understanding of the behavior of people in their environments.

Ambient intelligence has evolved at a great pace over the past ten years, from the early beginnings when the European Commission ISTAG group presented their

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DOI 10.1145/2378016.2378020 http://doi.acm.org/10.1145/2378016.2378020

vision for ambient intelligence [Ducatel et al. 2001] to research on the many applications realized from that vision. Ambient intelligence-based systems provide feedback to users and carry out specific actions based on observed patterns and preprogrammed algorithms. Some systems are also aware of their surroundings and can function independently, offering capabilities including “sensitive, responsive, adaptive, transparent, ubiquitous, and intelligent behavior” [Cook et al. 2009]. These two areas of assisted living and ambient intelligence are converging towards a new paradigm in social computing, called Ambient Assisted Living (AAL).

AAL systems have benefited from advances in sensor technology, hardware, software, and communication paradigms, to such an extent that AAL systems have gained market penetration into the home, medical, and occupational environments. AAL may be implemented to either replace or complement traditional methods of care. As technology becomes increasingly mobile, ubiquitous, and pervasive, it is of course likely that the wider population will become beneficiaries of AAL. Greater reliance is now being placed on these technologies which are being used to provide increased support to older people. The AAL systems have become more complex, intelligent, and, crucially, may be relied upon in the area of assisted living. Hence there is now a need to critically assess the quality of the data, information, and knowledge arising from these systems.

This article focuses on quality issues associated with such AAL systems, provides an overview of relevant research, and discusses the impact of quality requirements upon AAL systems. The article is organized as follows: Section 1 provides an introduction and overview, while Section 2 discusses AAL, the associated technologies, services and applications, properties of an AAL system and evaluates the quality issues that may occur. Section 3 outlines a conceptual multilayer model for AAL and discusses quality issues in the different layers of the model. Section 4 outlines an AAL scenario, overlaying components of the system against the conceptual model. Section 5 concludes the article.

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## 2. AMBIENT ASSISTED LIVING

AAL technologies help to extend the time that older people can live at home by “increasing their autonomy and assisting them in carrying out activities of daily life” [Wojciechowski and Xiong 2008]. They may be used to provide increased support in the home environment, [Cook et al. 2009; Sun et al. 2009], providing assistance and support during the day and night with the activities of daily living (ADL). AAL has the capacity to provide assistance with specific conditions such as dementia and empower people who may have disabilities. Within medical environments, systems may provide augmented health care services, patient data management, and decision support systems [Isern et al. 2010]. The services that AAL technologies may provide include functional, activity, cognitive, intellectual, and sensory support [Doughty et al. 2007]. Examples of functions that the AAL technologies may provide include alarms to detect dangerous situations that are a threat to the user’s safety, monitoring the health and wellbeing of the user, and the use of interactive and virtual services to help support the user. Other detailed accounts of ambient assistive technologies that may support this philosophy of use are outlined in Nakashima et al. [2010] and Sun et al. [2009].

An example of an AAL technology for wellbeing is a reminiscence system, which provides “a range of activities and traditional tools aimed at stimulating thoughts, feelings and memories of times gone by” [Alm et al. 2007; Mulvenna et al. 2009]. AAL technologies may be used for communication, enabling the user to keep in touch with family, friends, and care providers [Kleinberger et al. 2009], as well as in support of the night-time care of people with dementia using lighting, guidance, therapeutic intervention, treatment, monitoring, and reminiscence [Carswell et al. 2009]. The different sets of users who may receive a benefit from using AAL technologies are defined as the elderly and their caregivers, health professionals, as well as relatives and friends [Kleinberger et al. 2009]. Maier and Kempter [2009] examine the critical ethical issues that may arise from vulnerable groups making use of AAL systems. The equipment that is based in the home of the user includes control boxes, sensors, and actuators. AAL also relies upon a middleware architecture that may be distributed across different hosting services and service providers. The incorporation of activity recognition and reasoning algorithms enriches the AAL system with contextual knowledge. This adds significantly to the complexity, and hence suggests the need for quality control.

### 2.1 The Importance of Quality for AAL Systems

An AAL system may be used to distinguish an event—for example, a person wandering at night. Quality issues may have an effect on the properties of an AAL system. These properties may include real-time operation, the ability to react and respond to events as they occur by making use of data that has been gathered from different types of sensors including contact switches to measure state, passive infrared sensors (PIRs) to detect movement, thermostats to measure temperature, and cameras and microphones to interpret movement and sound. A lapse in data quality may result in false positive or false negative events being inferred, and this may have a profound effect on the real-time operation of an AAL system, as the resulting contextual knowledge may be incorrect. A solution may include verifying detected events, as they occur by carrying out pattern matching and determining the circumstances behind an event to ensure that it is representative of a true event and that the data being gathered by sensors is free from errors. This may enable accurate information to be built up that details events that have occurred and which sensors were involved. A lapse in quality at this stage may impair the reasoning and actuation properties and reduce the ability of the AAL system to determine what has occurred and carry out actions based on the current detected context. This may result in contextual knowledge that may not be fully representative of "what" has occurred and/or "who" has been detected by the system. This may affect the adaptive human computer interaction properties of an AAL system and prevent it from offering tailored interactions based on the user's current requirements, detected situation, and who they are.

A failure in quality may result in incorrect contextual knowledge being processed, a failure to anticipate a user's needs, not being able to provide worthwhile interaction, and not being able to adapt to changes that may occur in the environment. AAL systems and the relationship with context awareness have been outlined by Nakashima et al. [2010]. As discussed, AAL systems may operate in real-time as they may process events as they occur in the environment and provide immediate support based on these detected events. For example Zhu and Sheng [2010] describe a system that provides real-time tracking of older people to enable assisted living services. Poor-quality data may result in the system not being able to accurately detect the users' location, which may lead to an inadequate provision of care and assistance. AAL systems may make use of data fusion, where data may be combined from different sources such as hardware sensors and virtual sensors to produce a representation of what has occurred in the environment. Examples of AAL systems that make use of data fusion for activity recognition through fusion of motion and location data have been reported by Amoretti et al. [2010] and Zhu and Sheng [2010]. Poor-quality sensor data may again result in an incorrect representation.

### 2.2 The Impact of Quality Issues on All Architectures and Frameworks

Both external and internal factors may have a direct effect on the quality of the data being sent to the AAL system, the information that the AAL system derives from this data, and the contextual knowledge that may be formed from this data and information. Sensors in the environment may fail or provide incomplete or incorrect data that may lead to incomplete or erroneous information that may result in the AAL system not operating as expected [Stvilia et al. 2007].

Several AAL architectures and frameworks have been proposed in the literature including PERSONA [Avatangelou et al. 2008], SOPRANO [Wolf et al. 2008], and AMIGO [Georgantas et al. 2005]. Further examples include "an intelligent home middleware system based on context-awareness" as detailed by Chun-Dong et al. [2009] that consists of a context-collecting agent (CCA), context-reasoning agent (CRA), and a context-management agent (CMA). A degradation of contextual knowledge quality may have an impact on the functionality offered by the intelligent agents. For example, if the contextual knowledge collected by the CCA contains errors, then the contextual data sent to the other two agents, may result in untrue or erroneous events being processed. A multimodal pervasive framework for AAL is outlined by D'Andrea et al. [2009]. The system is able to interpret spoken dialogue and recognize user-issued commands, and undertake actions. A user wishing to know what is on television would issue the command "*I want to know what TV programs are on this evening*" rather than browsing a menu. The framework is personalized to the user's needs. Hristova et al. [2008] outlines a framework that provides context-aware services to an older person that is able to adapt to "changes in the environment and to adapt their behavior to the user's situation, needs and objectives." A reduction in the quality of the sensor data may have an impact on functionality of the contextual services. For example, the services may rely upon accurate location data. If the location data is inaccurate, then appropriate services may not be activated when they are required. Details of the environmental state including the light, temperature and the humidity are gathered through the use of small wireless devices with sensing and communication capacity called "motes". This data may be critical for ensuring that the user's environment is properly controlled. In relation to the amount of light that is detected, this may be useful for detecting whether curtains have been opened in a bedroom and in detecting possible issues if the curtains are still closed during the day. A degradation of the quality of the data being processed may result in false alerts being generated and the environmental conditions not being managed efficiently, as the context-acquisition processes starts with the sensor data that is sent by the sensors.

I-Living [Wang et al. 2006] provides activity reminders, vital sign measurement, behavior profiling, and emergency detection. Mission-critical services such as vital sign measurement and emergency detection rely upon a high-quality stream of data to ensure that changes are detected and false alerts are not generated. Poor-quality data may lead to poor quality information, for example the doctor may have erroneous information that states that the patient is currently in good health.

## 3. AAL SYSTEM MULTILAYER MODEL

As described earlier, AAL systems are complex, which makes it difficult to detect errors and quality issues when they arise. The tiered model in Figure 1 is intended to provide a conceptual backdrop against which the different quality issues can be explained.

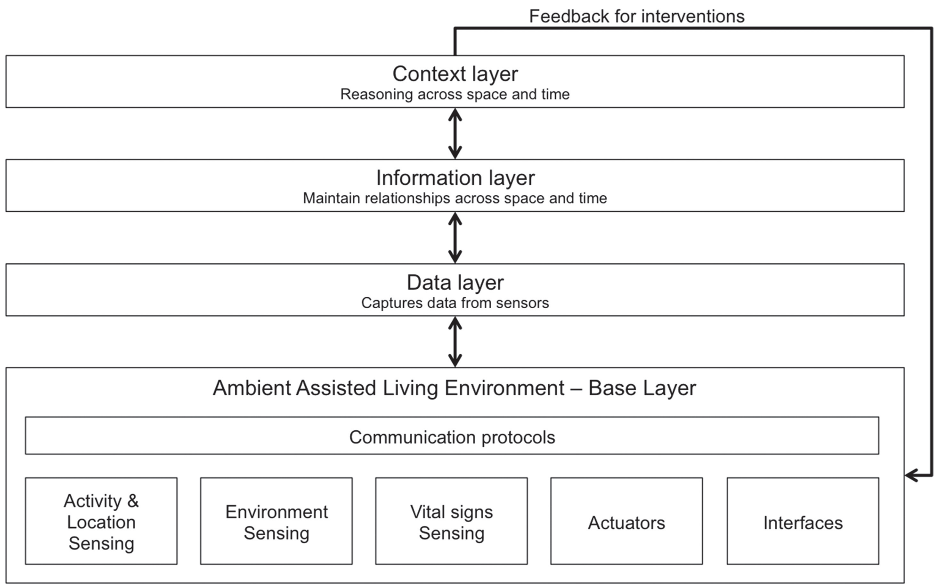


Fig. 1. Conceptual model of AAL system layers.

The base layer encompasses the AAL environment and is comprised of sensors and actuators that detect activities and events; environmental sensors to measure room temperature and humidity; body-worn sensors to monitor vital signs; location sensing to monitor the whereabouts of the person being observed and interfaces to enable interaction between the AAL system and the person. The next layer is the data layer, which provides a common platform for data storage. The two remaining layers are the information layer and the context layer. These layers rely on processing capability and interaction with a knowledge base, which may store information over time. Whereas software can be developed using a strict software engineering methodology, experience over many years in the software industry has shown that programmers rarely eradicate all potential bugs or unsafe (possibly unusual) cases. The following section describes quality issues in component parts and communication protocols in this base layer.

### 3.1 Quality Issues in AAL System Sensors

AAL systems have the ability to "track, record, analyze, correlate and interpret images, sounds and texts" [Rouvroy 2008] that may represent the activities that a user may carry out during the day and night. The sensor data that is consumed by AAL systems may come from several types of sensors including hardware sensors and virtual sensors (software applications and widgets) and the quality may be affected by the transition of data between software agents and/or services. Sensor factors that may have an effect on data quality may include the location of the sensor and environmental conditions such as temperature and humidity. As an AAL system may rely on the sensors to retrieve data on what is occurring in the environment, it may be important to consider further characteristics of sensors that may have an effect on quality. Table I outlines the quality issues related to sensors.

Table II to Table V highlight sensing technology and communication protocols that may commonly be used by an AAL system. In order to provide high-quality location and state data and be able to track a user's location for context-aware services, the data

Table I. Quality Issues Related to Sensors

| Factors | Possible effect on quality |
|---|---|
| Design | The sensors may have intrinsic design flaws that may produce errors such as anomalous sensor events. Using a sensor that is not designed for the particular scenario may mean that events are not detected. |
| Manufacturer | The manufacturer of the sensor may have an effect on quality, as manufacturing methods may reduce the length of time a sensor operates at full capacity. A sensor manufactured by a "budget" manufacture may fail before a sensor manufactured by a nonbudget manufacture, which may be due to the materials that have been used. There may be differences in quality control during the manufacturing process, and therefore there may be a larger number of sensors that do not work on first use or fail soon after. Well-known metrics such as mean-time between failures (MTBF) can be used to assess quality of individual components. |
| Calibration | Sensors that are not correctly calibrated may produce a data stream that contains erroneous readings and the sensors may not detect events that have occurred in the ambient environment. Over a period of time, the sensors may be prone to "sensor drift" and may need to be recalibrated. |
| Application | The application of the sensor may directly affect the quality of any data being recorded. With the example of body-worn sensors, if they are not placed in the correct area or not properly attached, then any data recorded from these sensors may be of poor quality. |
| Integrity | Sensors may be tampered with or accidently altered resulting in "untrue" data being recorded. |

Table II. Activity/Location Sensing - AAL Well-Being and Location-Based Services

| Sensing technology | Common use | Quality issues |
|---|---|---|
| Accelerometer/ Compass | Detect trips or falls based on the orientation of the user (vertical, normal, horizontal, may have fallen and be lying on the floor). | The user may lie down on a bed, sofa, or sit in a chair, this may confuse the accelerometer. This may result in false reading that may trigger an unneeded interaction and prompt. |
| Global Positioning System (GPS) | Determining the location of the user by making use of global positioning satellites. | GPS signal may be lost due to technologies not being designed to operate indoors. Inbuilt inaccuracy may have an effect on tracking a person in the confines of a "smart home environment". |
| Radio Frequency Identification Device (RFID) | May provide the name and identifiable details of the user. | An RFID is commonly low power and has a limited range; therefore an accurate "picture" of a user's activities and location may not be built up if the RFID fails or is not detected. |

that is generated by the sensing technologies may be combined through data fusion. Table VI highlights common interface technologies that may be used. In Table II, the sensing technology for monitoring and detecting activities and activity-related events is described. These are primarily related to movement and orientation detection using accelerometers and compass technology, geo-location calculation using global positioning systems (GPS) and item location technologies such as radio-frequency identification (RFID).

Table III outlines some of the communication protocols that may be employed in AAL systems that are prone to quality issues.

In Table IV, a range of environmental sensors is outlined. These include traditional movement-detection sensors; RFID used for item tracking and use of image or sound sensing to detect events.

Table III. Communication – Mobile and Wireless AAL Communication and Interaction

| **Sensing technology** | **Common use** | **Quality issues** |
|---|---|---|
| Global System for Mobile Communication (GSM) General packet radio service (GPRS) | Communicating with the user through a mobile interface. Providing access to the ambient intelligent system through a mobile device. | Availability of service, if the communication technology suffers a fault or the signal is lost, then the health professionals or care providers who are monitoring the AAL system may not receive accurate information. |
| Zigbee, WiFi, WiMax | May be used in wireless sensor networks to transmit sensor data between the sensor's and the AAL system. | An AAL system may be connected to a wireless sensor network, this may have an impact on the quality of the data and environmental obstacles such as walls may interfere with the signal. WiMax has a much stronger signal and may be able to overcome these obstacles. |

Table IV. Environment Sensing - AAL Assistance with Activities of Daily Living

| **Sensing technology** | **Common use** | **Quality issues** |
|---|---|---|
| Hardware-based sensors (including infrared, ultraviolet, sound and touch | May provide the ability to detect movement, the time of day, whether curtains have been opened. | Sensors may fail or detect a person other than the user. To overcome sensor failures, redundancy may be built into the sensor network. To enable successful identification of the user, tracking data from the sensor's detailed in Table I may be combined with data gathered from the motion sensors to ensure that the correct person has been identified. |
| Microphone | May detect sound in the ambient environment. | Microphones may be affected by mobile devices that may cause distortions. The microphone may not pick up the sounds that are being made by the user of the system. This may result in incomplete contextual knowledge. |
| RFID | May be used to track the use of objects, appliances and utensils. | RFIDs may be prone to failures; an RFID may become dislodged from an object or appliance. This may result in invalid contextual knowledge being formed as the use of objects, appliances, and utensils may not be detected. |

In Table V, examples of sensors for monitoring vital signs of a person are described. These include Electrocardiogram (ECG)-sensing, body temperature measurement as well as blood-pressure monitoring.

Table VI highlights several common types of interface technology that may be used to provide interactions between the user and the AAL system.

An AAL system may rely upon a user responding to prompts and asking for assistance through an interface. If this interaction does not take place or an incorrect interaction is carried out, then the resulting contextual knowledge quality may be affected.

### 3.2 AAL and Data Quality

An AAL system may process several different types of data including location, activity, medical, and health related data. In order for the system to work efficiently and effectively, it is important to ensure that this data is free from errors, as it may be depended upon to support safety-critical applications—as an example, an AAL health

Table V. Vital Signs - AAL Health Management and Monitoring

| Sensing technology | Common use | Quality issues |
|---|---|---|
| Electrocardiography (ECG) | Monitoring user vital sign such as heart rate. | User may remove sensors, and this may result in the data stream being interrupted. The sensor may fail resulting in erroneous readings being recorded. |
| Temperature | Monitor the temperature of the user. | The temperature may be affected by external heat sources, such as a radiator. |
| Blood pressure | Monitoring the blood pressure of the user. | The quality of readings may be affected by orientation of-the-cuff, sensor failures, human error or the user removing the sensors. |

Table VI. AAL Interface Technologies

| Interface technology | Common use | Quality Issues |
|---|---|---|
| Resistive/capacitive touch screen | Resistive and capacitive touch screens are used to provide a touch-based interface to a user. | Resistive touch screens may not correctly register that an interaction has taken place, as they rely on adequate pressure being applied to the screen. Capacitive touch screen may overcome this since a light touch is required, as they rely on a small electrical current to register a touch event. Not registering touch events may result in contextual knowledge that is incomplete. |
| Remote control | Remote controls may be used to control a TV-based interface. | Remote controls require a direct line of sight to the Infrared (IR) receiver. If this line of sight is broken, then interactions may not be registered |
| Voice | May be used to provide voice interaction between the AAL system and the user. | Voice commands may not be recognized or understood. |
| Motion capture | May be used to provide interaction, the user moves his limbs and this corresponds to a virtual interface on a screen. | Movements may not be recognized or another person may be mistaken for the user. |

system that monitors an individual's vital signs so that assistance and support may be offered. The AAL system may suggest taking medicines and carrying out actions based on this recorded data. In this case, poor data quality may have a serious impact on a person's health. Unsafe situations may be detected and the person being observed may wander during the night. If the data being sent by the sensors in the environment is of poor quality, the system may not detect that the individual is wandering and may not carry out actions such as turning on lights, and the individual may not be prevented from falling. The individual may require assistance with getting dressed, washing hands, or reminders to turn off a tap or an electrical appliance. A lapse in data quality may mean that the AAL system does not provide this required assistance and support. Lapses in data quality may have an effect on an individual's privacy, and there may be ethical issues arising from such a situation.

### 3.3 Measuring Data Quality

Data quality metrics for analyzing the quality of the data that is processed by an AAL system are detailed by Rajamani and Julien [2009], and include carrying out measurement of the number of sensor nodes participating in data queries, measuring

Table VII. Metrics for Measuring AAL System Data

| | |
|---|---|
| Accuracy | Accuracy may be checked by ensuring that data collected fits within set thresholds that may have been established during the testing of the AAL system. Errors may be caused by miss calibrations and sensor failures. |
| Confidence | Sensors in the ambient environment may be susceptible to vibrations, humidity, and other environmental conditions. The AAL system may be aware of the environmental conditions and the effect that these conditions may have on the data stream and carry out statistical analysis on the data to detect errors. This analysis may be used to determine the confidence that the data is free from errors. |
| Completeness | The data that is gathered by the AAL system may be used to determine what has occurred in the environment. Sensor failures or malfunctions may result in data that corresponds to events that have occurred in the environment not being detected, this may result in an incomplete picture being developed. |
| Data volume | An AAL system may consume a large volumes of sensor data, and it may be important to ensure that the AAL system is able to process this data efficiently so that it may respond to detected changes in the environment. |

the variance of the returned data samples and the locality of the data by measuring the location that the data has been gathered from. These may be relevant to an AAL system, as it may rely on accurate data to function correctly and may make use of data from various sources through data fusion. The AAL system may rely on high-quality data that originates from a sensor-streaming environment; such an environment is discussed by Klein and Lehner [2009]. Metrics that may be applied to an AAL system are outlined in Table VII.

Another method to measure the data quality of an AAL system may be to make use of data modeling. A data model that may be applied is outlined by Sha and Shi [2008], that is based on consistency analysis as frequency consistency, temporal, consistency, and numerical consistency. This may be relevant to an AAL system, as over a period of time the constancy of the data may be checked to ensure that no anomalies have occurred and to detect any unexpected changes. For example, an AAL system may monitor an older person for a number of weeks and gather constant data on the activities that he or she carry out and other aspects of their daily routine, if an unexpected variance occurs in the data, this may represent an erroneous event or a change in the older person's routine. The AAL system may be able to distinguish between these and issue an alert to a care professional or administrator if required.

### 3.4 AAL and Information Quality

An AAL system may transform the data that has been gathered from the sensors into information. Following the principles outlined by Bisdikian et al. [2009], this information may include why a sensor has been triggered; when it was triggered; where it was triggered; what the sensor event represents and the details of the event; who corresponds to the event; was it triggered by the user of the system or the system itself; and lastly how will the event be used. There are several information quality principles that may be directly relevant to an AAL system, including availability, integrity, and authentication. An AAL system may be required to have high availability, not suffer down time or crash, as it may be relied upon to offer help and support to vulnerable persons. The factors outlined in Section 3.2 may contribute to information quality. For example, the AAL system may produce medical information from sensor data that may include vital signs and temperature readings. If the person being monitored removes or tampers with the sensors, then the resulting information may be of poor quality, as the readings may be inaccurate or incomplete. Another method of ensuring information quality may be to adapt and apply information assurance principles to ensure that safeguards are in place to help ensure that the information is available and that there are no delays. The system must also have integrity, meaning reliability and completeness, at data-, information-, and system-levels. Finally, the information should only be processed by the AAL system and not by any other unauthenticated external sources. Implementing authentication mechanisms may help to ensure that this occurs. Authentication may also be used to ensure that the information has not been changed by external sources.

### 3.5 Measuring Information Quality

Information quality may be divided into three categories and each has associated metrics, as outlined by Stvilia et al. [2007]. These categories are intrinsic, relational, and reputational information quality. Intrinsic information quality "can be assessed by measuring internal attributes and characteristics," while relational information quality measures the relationships between information and how this information is used in the context of the system. Reputational information quality "measures the information entity". Information quality may be managed and measured by making use of information assurance techniques for analyzing the information integrity and ensuring that it is representative of what has been detected in the environment. Information assurance ensures that no external sources have interfered with the information. Metrics for measuring information quality include accuracy (how the observed information matches the reality of a current situation); certainty (measurements to ensure that the information recorded is certain to be correct); timeliness (measurement of the amount of information that is available); and integrity (measuring the integrity of the information to ensure that it has not been altered) [Hossain et al. 2007].

### 3.6 AAL and Contextual Knowledge

As an AAL system makes decisions based on the contextual knowledge that may correspond to activities and events that have been detected in the environment, it may be important to ensure that the contextual knowledge is of high quality. Errors that may result from lapses of knowledge quality may have a negative effect on the operation of an AAL system; this is discussed further by Alm et al. [2007]. Any contextual information comes associated with parameters, including precision of information, correctness probability, trustworthiness, and resolution. The quality of context is defined as "any information that describes the quality of information that is used in context information" [Buchholz and Schiffers 2003]. Acquiring context is not a straightforward task, due to its dynamic nature and the heterogeneous state of data sources. Context can be extracted from low-level sensors and high-level managers as well as derived from applications utilizing the network. It has been emphasized that the majority of context-aware applications use the data from the sensors later offline through data processing and features extraction [Mayrhofer et al. 2003]. There is no consensus for context representation (capturing, representing, and modeling context or quality of context). Context knowledge can be strongly heterogeneous and often incorrect, inconsistent or incomplete, and this may lead to quality issues.

### 3.7 Measuring Contextual Knowledge

In order to facilitate successful measurement of contextual knowledge quality, a set of measurement parameters may need to be followed. Examples outlined by Bu et al. [2006] include delay time and context correctness probability. Delay time is outlined as the interval between the time an event occurs and when it is recognized by the system, while the context correctness probability aims to overcome possible sensor data inaccuracies by measuring the contextual data using random sampling. Other parameters used include context consistency probability, using random sampling to ensure that the context information being recorded is consistent. Several metrics and parameters for measuring quality of context have been put forward, which follow information quality parameters; information quality indicators; information quality attributes; an information quality indicator value; an information quality parameter value; and information quality requirements [Razzaque et al. 2005]. In many AAL systems, the identification of ADLs by the inhabitants of a house is of particular value. Such systems use various means to gather contextual information about the behavior of the inhabitants. In one system, probabilistic models are used to manage uncertainty and incompleteness of data as the ADLs are generated. In this work, the models use Dempster–Shafer theory of evidence to combine data about behavior into probability-based profiles and identification of activities [Hong et al. 2009]. How AAL systems can embrace such mathematical models of context awareness and identify context quality in such systems is a key research question.

## 4. ILLUSTRATING QUALITY ISSUES WITH AN AAL SYSTEM SCENARIO

In order to provide some insight into how quality may have an effect in an AAL system and the methods that may be used to measure quality, a scenario extract is provided.

Bob is 68 and lives alone in his bungalow home. The rooms in his home include a living room that leads to a hallway and a small dining area that is next to a mid-sized kitchen. In the kitchen there is an old-style four-ring gas cooker, fridge, microwave, kettle, toaster, and a large sink. The bungalow has two bedrooms, the larger one that is occupied by Bob and a smaller guest bedroom that is used by relatives who occasionally come to visit. Lastly, there is a bathroom with the usual amenities. Relatives visit around once a week, and sometimes stay over for a weekend (at least once a month). The relatives live 150 miles away and are concerned about Bob being alone in his house. They have suggested that Bob move into residential housing; but Bob enjoys his independence and does not want to give up his dog and other benefits of living independently. Bob's dog enjoys sleeping on Bob's favorite recliner chair and on Bob's bed when he is not using it. Bobs daily activities may include watching TV, listening to the radio, and looking through family photo albums.

From this scenario extract it may be possible to infer the types of assistance and support that may need to be provided by an AAL system and the types of data, information, and knowledge that may be consumed and processed by the AAL system. From this example scenario, an AAL architecture that may be devised is shown in Figure 2, overlaid on the multilayer models described in Section 3. How data, information, and knowledge quality may be applied to the AAL architecture is discussed in the subsequent paragraphs.

The sensors (B) constantly monitor the environment where a person (A) is situated. Sensor failures at this stage (1) may result in poor quality sensor data being sent to the sensor agent (C). The data quality principles outlined may be applied to ensure that sensor failures and erroneous sensor events are detected. The sensor agent may determine how accurate the sensor data is by examining the sensor data through the use of algorithms to detect anomalous data and inconsistencies. Once error checking has been carried out and the sensor agent is confident that the raw sensor data is free from errors, the data may be transformed (3) and sent to the (E) context management agent. The information may include which sensors have been activated; what the readings are from the sensors, and the time that the sensors where triggered. At this stage, information quality principles may be applied to ensure that the information derived from the sensor data is of high quality by determining the accuracy of the information and that it corresponds to true sensor events that have occurred in the environment, and how confident the agent is that the information is accurate. Other issues include: *timeliness*, has the information been received in a timely manner and

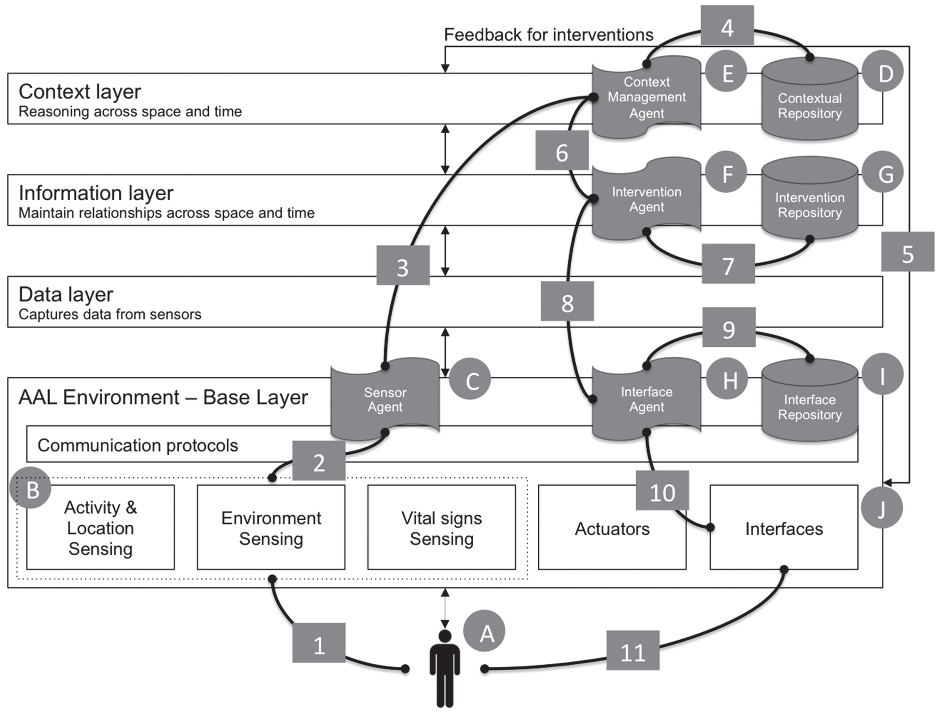


Fig. 2. Example AAL system architecture.

is it still representative of the events that have occurred in the environment? Also, the *integrity* of the information, has it been received from the sensor agent or has it been provided by an external source. From the information that has been gathered, concepts such as the "6W framework" outlined by Augusto and O'Donoghue [2009] or the "W4" model [Castelli et al. 2006, 2007] may be used to provide an insight into how contextual knowledge is formed (4) by the contextual management agent. The contextual knowledge may include who triggered an event; where the event occurred; when it occurred; what triggered the event; why it has occurred; and how should a response be made. The quality of the contextual knowledge may need to be ensured so that the intervention knowledge (what will occur, how will a response be made, etc.) that may be formed by the intervention agent (F) is accurate. Feedback for the interventions may occur at stage (5). Knowledge checking may occur between stages 6-8, where the contextual knowledge and intervention knowledge may be checked and processed. The (H) interface agent to determine the content of the interface so that interventions may be carried out. The information that may be displayed through the Interface (J) is determined by the interface agent (9) and then sent to the interface (10). Any lapses of previous data, information, or knowledge quality may result in the information being presented (11) to the person (A) that is not accurate and is not representative of the assistance and support that is required.

A lapse in sensor data, information, or contextual/intervention knowledge quality may have a serious impact on the functioning of the AAL system. For example, poor data quality that results from faulty sensors or erroneous events being detected at step (2) may prevent the sensor agent from processing true sensor events and sending high-quality sensor information to the context management agent. Poor data, information, or knowledge quality may have an effect on the other agents, resulting in a cascade effect as software agents may not act as expected, and this may mean that the AAL system responds to erroneous events, offers the wrong assistance or support or puts the individual at risk. To help guarantee that the software agents receive high-quality data, information and knowledge algorithms may be implemented to measure the quality, and when a lapse of quality is encountered, carry out a particular action. For example, if the sensor data being received by the sensors agent is detected to be of poor quality, then an administrative alert may be generated and backup sensors may be activated to aid in determining the causes in the lapse of data quality.

## 5. CONCLUSIONS

From conducting research into the operation of AAL systems, it is apparent that obtaining quality-assured data from the sensors located in the environment is the major contributing factor to maintaining quality of information and contextual knowledge. The data that is gathered may be transformed into information describing an appliance, object, utensil, or individual. The information may then be transformed into contextual knowledge that corresponds to a particular event or activity that may have been carried out. Poor-quality data therefore results in poor-quality information, which in turn leads to poor-quality contextual knowledge. Data, information, and contextual knowledge quality are closely linked, and a failure in one adversely impacts the others. If the AAL system then makes an intervention based upon incorrect inputs, then the person availing of the services may suffer.

AAL systems research draws upon many areas of information systems and communications technology, and the resulting architectures for the AAL systems reflect the complexity of ambition of the research and development of the state-of-the-art, as outlined by Nakashima et al. [2010]. However, it is apparent that such AAL systems are beginning to emerge from the research laboratories with plans for mainstream application in five to ten years. Examples of these systems include PERSONA, SOPRANO, and AMIGO.

A multilayered conceptual model was introduced against which the quality issues in AAL systems were examined. In the base layer, redundant data streams may be used to aid in overcoming errors that may have a negative impact on the AAL system's performance, resulting from sensor failures and communication errors, so that in the presence of errors, a reasonable decision can still be inferred. In an AAL system, we propose that context can be used and fed back to quality-assure the data, allowing the system to degrade gracefully when it is subject to sensor or communication irregularities. However, it is necessary that such quality-control measures are designed into the systems. By following such a model it may be possible to ensure that lapses in quality do not have a negative effect on the operation of an AAL system.

Populations are aging, and there will continue to be a need to develop new means to support and care for people and to ensure that their quality of life and wellbeing is preserved within economies of health and social care systems. AAL and the area of ambient intelligence may represent the best area of research to develop the means to satisfy the outlined requirements, and therefore we suggest that future research should be conducted in these areas. The technology of these systems is evolving and there is a need to carry out research into the assessment of data, information, and contextual knowledge quality to ensure that any new technologies function efficiently and effectively, so that the safety and wellbeing of the people using them may be preserved.

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Received November 2010; accepted January 2012